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Wind-resistant design theory and safety guarantee for large oil and gas storage tanks in coastal areas

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Abstract

Large oil and gas storage tanks serve as crucial industrial energy infrastructures, which are usually thin-walled steel structures with large volumes and light weights, and they are sensitive to wind loads. Under the influence of strong winds or typhoons, large oil and gas storage tanks may suffer wind-induced damage, resulting in the leakage of gas or liquid inside the tanks, posing hazards to the ecological environment and public safety. Therefore, it is of great theoretical and engineering significance to research the wind resistance of large oil and gas storage tanks. This paper provides a comprehensive review of key issues in wind resistance for large oil and gas storage tanks, including characteristics of flow around circular cylinders, wind effects on structures with circular cross-sections, near-surface wind field characteristics, wind effects on large oil and gas storage tanks, wind-induced interference effects, structural dynamic characteristics, wind loads and wind-induced response calculations, multiple load effects, and wind-induced vibration control. The deficiencies of current research are summarized. The prospects for research on the design theory and safety assurance of large oil and gas storage tanks are presented through various methods, including field measurements of near-surface wind fields and wind effects, wind tunnel tests utilizing aeroelastic models, numerical simulations involving fluid–solid coupling, theoretical analysis, and machine learning.

Keywords: Coastal area, Large oil and gas storage tank, Wind load, Wind-induced response, Structural dynamic characteristics, Wind-induced vibration control

1 Introduction

Large gas tanks and oil storage tanks are important industrial energy infrastructures, which play an important role in social production and development. Gas tank is a kind of steel tank for storing gas, which is widely used in steel production, civil gas and chemical industry [1]. It has the function of storing gas, stabilizing the pressure of pipe network, ensuring the safety of pipe network and improving gas efficiency [2]. Oil storage tanks are mainly steel storage tanks for storing crude oil and crude oil products, which are widely used in refining, chemical industry and oil depots, and play an important role and are of strategic significance in stabilizing the relationship between oil supply and demand, calming oil prices and coping with emergencies [3]. Large gas tanks and oil storage tanks (collectively referred to as large oil and gas storage tanks) have similar structural characteristics. They are cylindrical and primarily made of lightweight, thin-walled steel structures, characterized by large volume, high flexibility, and low damping. With the development of social economy, the types, quantities and capacities of gas tanks and oil storage tanks are increasing. The development history of representative large oil and gas storage tanks is shown in Table 1.

Compared with traditional concrete structures, large oil and gas storage tanks are wind sensitive structures. Under the action of wind load, local vibration and deformation of oil and gas storage tanks are significant, and they are prone to wind-induced damage such as buckling of tank walls or overall collapse. Large oil and gas storage tanks are typically constructed in coastal areas, where strong winds or typhoons occur frequently. This repeated exposure to internal pressure and external wind loads often results in wind-induced damage to these tanks. The common forms of wind-induced damage are shown in Fig. 1. Once wind-induced damage occurs to oil and gas storage tanks, it will cause internal gas or liquid leakage, which seriously endangers the ecological environment and social public safety [7]. Therefore, it is of great theoretical and engineering significance to research the wind resistance of large oil and gas storage tanks.

2 Wind resistance of circular section structures

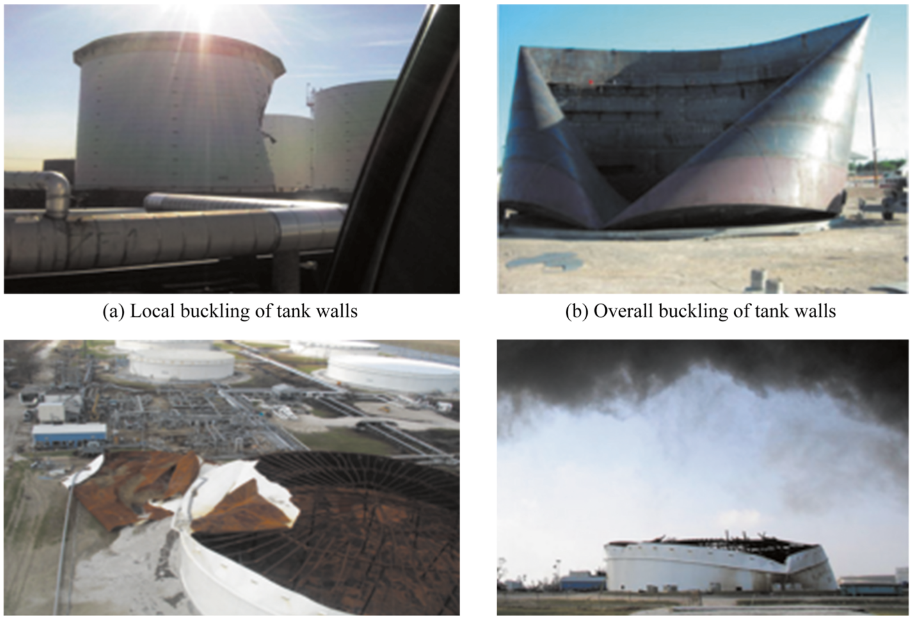
The shape of the oil and gas storage tank is cylindrical, which can be simplified into a circular cross-section structure for research. The current research on wind resistance of circular cross-section structures has achieved certain results.

2.1 Flow characteristics around cylinders

The flow around cylinders is a classical problem in fluid mechanics, and its wake characteristics are directly related to the load state of the cylinder [8, 9]. The cylinder is a nonlinear object, and its flow characteristics and stress state are influenced by factors such as surface roughness, cylinder size, and Reynolds number. Coutanceau et al. [10] studied the relationship between the wake of cylinders and the Reynolds number, discovering that at low Reynolds numbers, the fluid flow remains stable, while at high Reynolds numbers, the flow becomes predominantly turbulent. The wake characteristics of the cylinder at different Reynolds numbers are shown in Table 2.

Table 1 Development history of large oil and gas storage tanks [1, 4–6]

Large gas tanks			**Large oil storage tanks**		
Time	**Company**	**Type**	**Time**	**Location**	**Volume ($\times 10^4$ m^3)**
1885	Japan Fuji Steel	Blast furnace	1962	America	10
1915	Germany M. A. N	M. A. N	1967	Venezuela	10
1927	Germany Klonne	Klonne	1971	Japan	16
1947	American GATX	Wiggins	1975	Shanghai, China	5
1980	Shanghai Baosteel	M. A. N	1985	Qinhuangdao, China	10
1985	Mitsubishi Heavy Industries	COS	2004	Maoming, China	12.5
2005	China Ansteel	New dry type	2004	Yizheng, China	15
2015	China Luoyuan Mingguang Steel	Single-stage	2008	Shanghai, China	15



(a) Local buckling of tank walls (b) Overall buckling of tank walls

(c) Damage to the tank roof (d) Roof failure and wall buckling of tank

Fig. 1 Wind-induced damage forms of large oil and gas storage tanks

Table 2 The wake characteristics of the circular cylinder at different Reynolds numbers [9, 10]

Reynolds number (*Re*)	Flow phenomenon and vortex shedding state
$Re < 5$	The flow does not separate, and no vortex is created
$5 \leq Re < 40$	The flow separates from both sides, forming a recirculation zone downstream of the cylinder composed by two symmetric stationary vortices
$40 \leq Re < 150$	The flow separates from both sides, forming alternating shedding vortices and maintaining a laminar flow state
$150 \leq Re < 300$	The vortex begins to transition from laminar to turbulent flow, and the boundary layer is laminar before separation
$300 \leq Re < 3 \times 10^5$	The whole vortex street gradually changes to turbulent state, and the boundary layer is still in laminar state before separation
$3 \times 10^5 \leq Re < 3.5 \times 10^6$	The boundary layer before separation is turbulent, leading to turbulent separation, a narrow wake, and irregular vortex shedding
$3.5 \times 10^6 \leq Re$	The turbulent vortex reappears

The Reynolds number significantly affects the flow characteristics around a single cylinder and the forces on the cylinder's surface. Scholars have conducted research on the flow characteristics of cylinder wake at different Reynolds numbers. Yuan [11] and Duan and Wan [12] utilized large eddy simulation to study the flow characteristics around a cylinder. When the Reynolds number is high, it is necessary to utilize a three-dimensional computational model [12]. Singh and Mittal [13] investigated the flow around a cylinder within the Reynolds number range of 10^2–10^7 by numerical simulation. The results indicate that shear layer vortices play a major role in the transition of the boundary layer from laminar to turbulent flow. Persillon and Braza [14] investigated the flow around a cylinder within the Reynolds number range of 100 to 300 and established the relationship between the maximum spectral amplitude and the Reynolds number. Gao et al. [15] studied the airflow patterns and surface pressure distribution on a cylinder by placing a short splitter plate upstream to alter the flow conditions and wake vortex modes. The flow around a single cylinder is not common in practical engineering. Large cooling towers, gas and oil storage tanks with similar circular section structures are typically arranged in clusters. Compared to the flow around a single cylinder, the flow around multiple cylinders is more complex, with factors such as Reynolds number, spacing ratio, and arrangement affecting the flow characteristics. Lam et al. [16] conducted numerical simulations using the finite volume method to study four cylinders at different Reynolds numbers and spacing ratios, revealing three flow patterns: stable shielding flow, swinging shielding flow and vortex shedding flow. Gong et al. [17] used the Boltzmann method to simulate the flow around four cylinders arranged in a diamond configuration at low Reynolds numbers, investigating the flow patterns and force characteristics under various spacing ratios. Guo et al. [18] studied the surface pressure distribution of tandem double cylinders at different spacings when the Reynolds number was $Re = 2 \times 10^4$ and analyzed the fluctuating lift and drag between the front and rear cylinders. Liang et al. [19] studied the flow around a group of six cylinders arranged in a tandem configuration at low Reynolds numbers and found that increasing the spacing made the flow more asymmetric, leading to vortex shedding.

The flow characteristics around a cylinder affect its flow field and forces. The existing research mainly relies on numerical simulations to investigate the wake characteristics and force properties of single and multiple cylinders under various Reynolds numbers. There are few studies on the flow characteristics around groups of cylinders under the action of unsteady flow conditions. In the future, the flow characteristics around cylinders with different diameters, spacing and arrangement under unsteady flow conditions can be studied.

2.2 Wind effects on circular cross-section structures

Wind tunnel test is one of the effective methods for studying the distribution of surface wind pressure on structures. Nishimura and Taniike [20] studied the pressure distribution coefficients of cylinders at subcritical Reynolds numbers through wind tunnel tests and explained the mechanism of lift pulsation caused by vortex shedding and flow around the cylinder. Li et al. [21] measured the wind pressure distribution of rigid cylindrical shell models with three different length-to-diameter ratios through wind tunnel experiments. They analyzed the influence of fluctuating wind loads on the ultimate load-bearing capacity of the structures. Li et al. [22] and Zhao et al. [23] studied the aerodynamic pressure distribution on the surface of large cooling towers and found that changing external surface roughness, adjusting wind speed [22], and using uniform grid lines [23] are effective methods for simulating the Reynolds number effect. Shen et al. [24] studied the wind-induced interference effects of two cooling towers through wind tunnel tests. Huang et al. [25] compensated for the Reynolds number in the wind tunnel test model of a circular arch greenhouse by attaching full-length meridional strips.

Scholars have also carried out studies on the wind effects of circular cross-section structures through numerical simulations and field measurements. Szczepaniak and Padewska [26] conducted numerical simulations to study wind loads on horizontal and tilted cylindrical structures, proposing an estimation method for wind loads on the surface of a straight cylinder. Yuce and Kareem [27] analyzed the flow around cylinders and square columns using CFD and found that the shape of column significantly influences the flow field. Bao et al. [28] studied the average wind load distribution of hyperbolic cooling towers through numerical simulation, obtaining three-dimensional flow field characteristics on both the inner and outer surfaces of the towers. Han et al. [29] studied the flow characteristics, wind pressure coefficients, and lift and drag distribution characteristics of super-large cooling towers under the influence of downburst unsteady wind fields using the impinging jet model and large eddy simulation. Wang et al. [30] conducted field measurements to study the wind-induced response of large cooling towers under strong wind conditions, discussing resonance effects, non-Gaussian characteristics, and non-stationary behaviors of wind-induced effects at realistic Reynolds numbers for large cooling towers. The results show that the wind-induced response of large cooling towers exhibits stable evolutionary characteristics in terms of frequency and non-stationary evolutionary characteristics in terms of intensity. Zhao et al. [31] conducted long-term on-site observations of dynamic and static wind pressures on the surface of cooling towers using dynamic pressure monitoring equipment. They established a relationship formula for the dynamic flow characteristics of the tower surface without considering interference effects.

Scholars have studied the pressure distribution patterns, group interference effects and Reynolds number effects on the surface of circular cross-section structures through wind tunnel tests, numerical simulations and field measurements. The research findings can provide references for the wind resistance in similar structures such as oil and gas storage tanks. However, circular cross-section structures like large cooling towers and oil and gas storage tanks still have differences in structure and function. Oil and gas storage tanks contain gases or liquids, requiring consideration of factors such as internal pressure. Therefore, the research findings of wind resistance in circular cross-section structures may not be completely applicable to oil and gas storage tanks.

3 Wind-resistant design theory for large oil and gas storage tanks

3.1 Measurement of near-surface wind field

It is of great significance for accurately evaluating the wind loads and wind effects of wind-sensitive structures and carrying out the wind-resistant design to carry out measurements of the near-surface wind field. Scholars have carried out research on characteristics of near-surface wind fields under different topography features and wind climates using anemometer towers, wind masts, and wind radar and UAV wind measurement systems. They have achieved some results, as shown in Table 3.

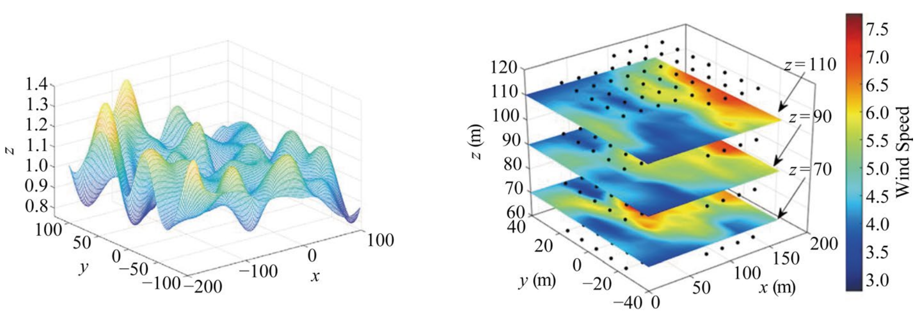
Currently, wind field measurements still lack comprehensive measurements of complete wind profiles and turbulence characteristics within the structural height. Existing results are primarily utilized for assessing the wind effects on infrastructure such as buildings and bridges, with fewer applications to evaluate wind effects on large oil and gas storage tanks and tank farms. The traditional anemometer tower has fixed measured position, limited measured height layout and high measured cost, so it is difficult to obtain the characteristics of the three-dimensional wind field in the whole space where the research object is located. Wind radar is suitable for high-altitude measurements, but

Table 3 Measurement of near-surface wind fields

Authors	Methods	Wind types	Results
Hui et al. [32]	Anemometer tower	Typhoon and benign wind	The characteristic parameters of wind field such as wind turbulence and power spectrum at Stonecutters Bridge in Hong Kong were studied
Li et al. [33]	Anemometer tower	Benign wind	The near-surface wind field characteristics of a power plant in Beijing were measured and compared with the wind load specifications of America, Japan and Europe
Huang et al. [34]	Anemometer tower	Windblown sand	The wind field within 10 m near the ground in desert area was measured, and the characteristics of windblown sand flow field in desert photovoltaic power station were summarized
Tamura et al. [35]	Wind radar	Strong wind and benign wind	Field measurements of wind fields at coastal and inland sites indicated that average wind speed and turbulence intensity profiles can be represented by exponential laws
Li et al. [36, 37]	UAV wind measurement system and anemometer tower	Benign wind	The boundary-layer wind field was measured. The wind profiles, wind direction angles, turbulence intensity and gust factors were analyzed, and the results measured by UAV and anemometer tower were compared
Huang et al. [38, 39]	UAV wind measurement system	Benign wind	The wind field characteristic parameters of three typical landforms in tropical island areas were obtained, and the reliability of wind measurement by UAV was verified
Shiau et al. [40]	Anemometer tower	Strong wind	The strong wind turbulence and wind speed spectrum of Keelung in Taiwan were measured, revealing a good fit between the measured downwind wind spectrum and the von Karman spectrum
Sparks and Huang [41]	Meteorological station, radiosonde and Doppler radar	Tropical cyclone	The gust factors at nearshore, coastal and inland stations were analyzed, revealing that the wind speed characteristics of tropical cyclones are essentially the same as those of extratropical cyclones
Yao et al. [42]	Wind radar	Typhoon	The fluctuating characteristics of the near-surface wind field were measured during the landfall of Typhoon Haima. The fitting relationship between gust factors and turbulence intensity was given

Table 3 (continued)

Authors	Methods	Wind types	Results
Li et al. [43]	Transmission tower	Typhoon	They studied the variation patterns of average wind speed, turbulence intensity, and gust factor profiles, and found that the variation of average wind speed with height aligns well with both the exponential law and logarithmic law models
Li et al. [44]	Wind mast	Typhoon	The characteristics of the near-surface wind field during the landfall of the violent typhoon Hagupit were studied, and it was found that the measured wind speed spectrum was in good agreement with the von Karman spectrum
Hu et al. [45]	Anemometer tower	Strong wind	Based on the nearshore wind speed data, the near-surface mean wind and turbulence intensity profiles were analyzed It was found that the mean wind profile in the near-surface boundary layer followed either an exponential or logarithmic law, and the mean turbulence intensity profile followed an exponential law



(a) Wind speed ratio at a specific height plane above complex terrain

(b) Wind speed field prediction based on UAV measured data

Fig. 2 Measurement and prediction of wind speed fields using UAV measurement systems

it comes with high equipment costs and low spatial resolution, thus posing certain limitations on its ability to measure near-surface wind fields. The UAV wind measurement system has many advantages, such as simple operation, flexible mobility, vertical takeoff and landing, accurate positioning, fixed-point hovering, and low cost. It has significant advantages in the field of wind profiles, planar wind fields, and three-dimensional wind field measurements in complex landforms. This system offers new perspectives and methods for the accurate measurement of wind fields around large oil and gas storage tanks and tank groups. Figure 2a shows the wind speed ratio at a specific height plane above complex terrain, obtained using a UAV-based wind field measurement system.

The fluctuations in wind speed ratio reflect the influence of terrain complexity on the wind speed field. The results indicate that as terrain complexity increases, the fluctuations in wind speed ratio above the corresponding area also increase. Figure 2b depicts the prediction of wind speed fields at various height planes based on UAV wind speed measurements, reflecting how terrain influences wind speed fields at different heights.

Obtaining the characteristics of the near-surface wind field at the location of large oil and gas storage tanks, as well as within the tank groups, provides a reliable wind field environment for subsequent numerical simulations and wind tunnel tests. This is a prerequisite for accurately assessing wind effects on oil and gas storage tanks and for conducting wind-resistant design.

3.2 Wind effects on large oil and gas storage tanks

3.2.1 Field measurements

Field measurement is the most direct and accurate method for studying wind effects on structures. Li et al. [46, 47] measured the wind-induced response of a large gas tank under typhoon conditions. They found that the distribution of acceleration response along the tank was symmetrical on the whole, with the top of the tank experiencing greater acceleration than the bottom. Additionally, they fitted a curve to determine the relationship between wind speed and acceleration at a 0° wind direction. Hu et al. [48] carried out field measurements of wind effects on a large coastal gas tank and obtained the wind pressure and wind vibration coefficient through analysis and calculation. Li [49] obtained the characteristics of near-surface wind field and wind pressure of the gas tank through field measurement, analyzed the acceleration response of the tank, and summarized the relationship curve between wind speed and acceleration response at specific wind angles. Li [50] conducted field measurements to study the average wind pressure coefficient and the fluctuating wind pressure coefficient of the gas tank, comparing them with results from wind tunnel tests. The comparison of average wind pressure coefficients between field measurements and wind tunnel tests is shown in Fig. 3. It can be seen that the field measurement and wind tunnel test results are generally consistent, but at some measuring points, the measured negative pressure exceeds those observed

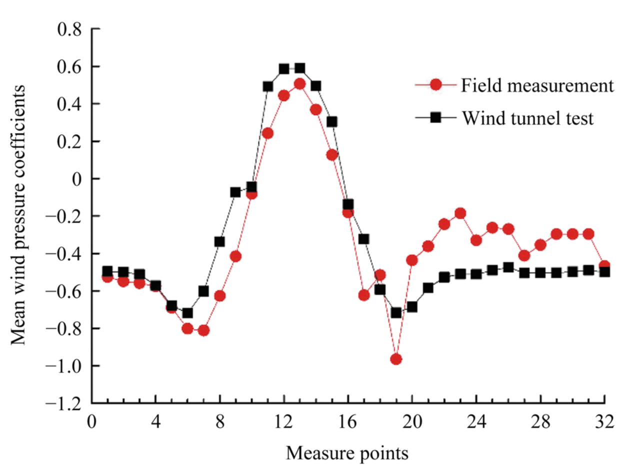


Fig. 3 Comparison between wind tunnel test and field measurement results of average wind pressure coefficient at a wind direction angle of 135° [50]

in wind tunnel tests. This discrepancy may be attributed to Reynolds number effects and differences between simulated wind conditions in the wind tunnel and actual field conditions [50].

Currently, there are limited field measurements concerning the wind effects on large oil and gas storage tanks. A few studies have measured characteristics such as surface wind pressure distribution and acceleration response of the tanks. However, the wind effects on oil and gas storage tanks vary across different regions and wind conditions. It is necessary to conduct field measurements for oil and gas storage tanks in different regions and wind environments, including their group wind effects. This can enrich the database of field measurements for large oil and gas storage tanks under strong wind or typhoon conditions.

3.2.2 Wind tunnel tests

Researchers [50–52] have studied the surface wind pressure characteristics of oil and gas storage tanks through wind tunnel experiments. They found that the distribution pattern of average wind pressure coefficients obtained from wind tunnel tests generally aligns with field measurements [50]. They believe that directly applying the shape coefficients in the design specifications tends to be conservative [51]. They also suggest that using distributed I-beams and surface roughness treatments can reduce the impact of Reynolds number effects on surface wind pressures [52]. The average wind pressure coefficients of the storage tank at a 180° wind direction angle are shown in Fig. 4. The variation trends of average wind pressure coefficients at different heights of the storage tank are basically consistent. At the eighth level (top of the tank), all values are negative, possibly due to wind flow separation at the tank's top, resulting in larger negative pressure vortices below the top edge [50]. Zheng [53] carried out wind tunnel tests on a large gas tank, measured its wind pressure coefficient distribution under turbulent conditions, and discussed its dynamic wind load based on the dynamic characteristics, without considering the influence of Reynolds number effects. Some scholars have also carried out wind tunnel tests considering Reynolds number effects. Guo [54] studied the Reynolds number effects on low cylindrical structures and the wind load characteristics of large

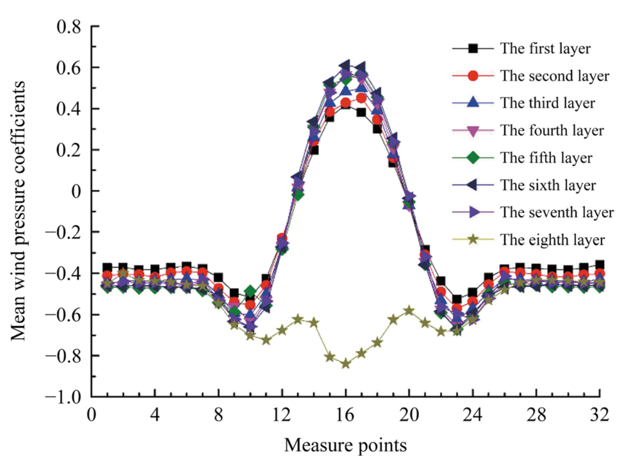


Fig. 4 Average wind pressure coefficients of the storage tank at a wind direction angle of 180° [50]

steel storage tank through rigid model pressure tests. Liu [55] conducted wind tunnel tests on a MAN type dry gas tank, analyzing the wind-induced vibration response of the structure under conditions that comprehensively considered Reynolds number effects and surface roughness. The rigid tank model without considering Reynolds number effects is shown in Fig. 5a, the tank model considering Reynolds number effects is shown in Fig. 5b, and the aeroelastic tank model considering wind-induced vibration effects is shown in Fig. 5c. Portela and Godoy [56] conducted wind tunnel tests on steel storage tanks based on rigid scale models, obtained the wind pressure distribution on the tank surface, and analyzed the wind-induced buckling of the tank with geometric defects and thickness reduction. Matsui et al. [57] measured the wind pressure distribution on cylindrical storage tanks through wind tunnel tests, utilized the measured data to predict the wind-induced dynamic response of storage tanks' floating roofs, and found that wind load would induce significant bending stress.

Current wind tunnel tests on large oil and gas storage tanks primarily focus on investigating the distribution patterns of surface wind pressure using rigid scale models, with fewer experiments conducted using elastic models. There are few researches on wind-induced vibration of gas tanks considering the piston's vertical movement and storage tanks of varying liquid levels. In wind tunnel experiments, the model scale ratio is relatively large, making it difficult to fully simulate the near-surface wind field characteristics of the actual conditions. The dimensions of the outer surface panels of oil and gas storage tanks become extremely small after scaling down, posing challenges for the manufacturing process to meet similarity ratio requirements, thus impacting the accuracy of experiments. Moreover, as oil and gas storage tanks approximate cylindrical spatial structures, the handling of surface roughness affects their Reynolds number effects, further influencing test accuracy.

3.2.3 Numerical simulations

Zou et al. [58] utilized the finite element method to study the impact of internal and external pressure differences on the wind-induced vibration response of gas tanks. Hsaine and Franklin [59] conducted numerical simulations to study the structural performance of dome-roof tanks under different loading conditions such as wind loads and snow loads. Li et al. [49, 60] developed finite element models for gas tanks with and without covers. By comparing the simulation results with field-measured measurements,

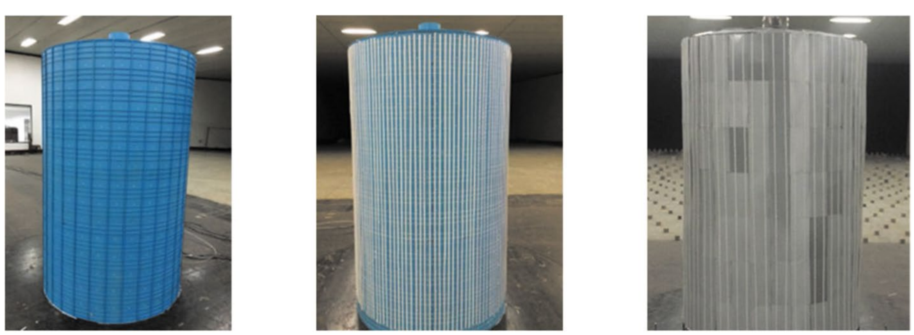


Fig. 5 Wind tunnel test models of oil and gas storage tanks [55]

they discovered that the dynamic characteristics of the uncovered model matched the measured data more accurately. This provides a valuable reference for wind-resistant design of similar structures. Zhao and Lin [61] conducted a study on the wind-induced buckling behavior of open-top steel storage tanks using finite element simulation. They found that the tank's height-to-width ratio, wall thickness, and whether it contained liquid all affected its wind-induced buckling resistance. Large gas tanks contain special components such as pistons. Scholars have conducted numerical simulations to study the wind-induced response [62], structural dynamic characteristics [63] and vibration mode distribution [64] of gas tanks with pistons at different heights. They found that the piston position significantly affects the dynamic characteristics of the gas tank.

Wang [5] and Bu et al. [65, 66] established finite element models to analyze the buckling behavior of oil and gas storage tanks, investigating the impact of stiffening ribs, wind rings and wind beams on the tanks' wind resistance. Sun et al. [67] utilized Large Eddy Simulation (LES) to investigate the effects of Reynolds number and liquid level on the wind pressure distribution of external floating roof tanks. The results indicate that when the Reynolds number exceeds 10^6, the wind pressure coefficients on the outer and inner walls of external floating roof tanks vary little with Reynolds number, while the liquid level has a significant impact on the wind pressure distribution on the tank. The instantaneous vorticity fields of flat-top and open-top storage tanks simulated using LES and RANS are shown in Fig. 6. The average pressure coefficients on the outer wall of the storage tank at different Reynolds numbers are shown in Fig. 7. As the Reynolds number increases, the external wind load on the windward side of the tank changes little, while the external wind load on the leeward side slightly increases. Zhao et al. [68] studied the variation of shell buckling loads with liquid level height through numerical simulation and experiments. Chiang and Guzey [69] utilized finite element analysis to study the geometrical nonlinear dynamic response of open-top storage tanks under wind loading.

Numerical simulations of wind effects on large oil and gas storage tanks have been widely conducted. Most existing finite element models of oil and gas storage tanks are based on rigid simplifications. There are relatively few numerical simulation methods that consider the fluid–structure coupling effects between the tanks and the incoming flow. The turbulence models for numerical simulation have some problems such as computational complexity and insufficient predictive accuracy, so it is necessary to

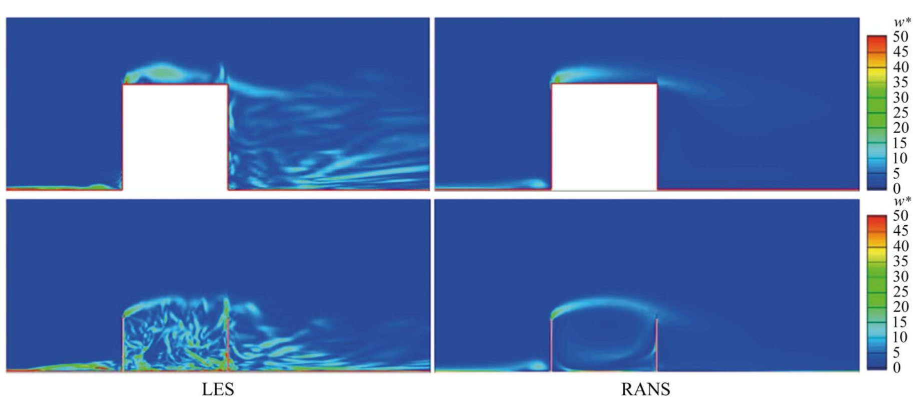


Fig. 6 The instantaneous vorticity fields of flat-top and open-top tanks simulated using LES and RANS [67]

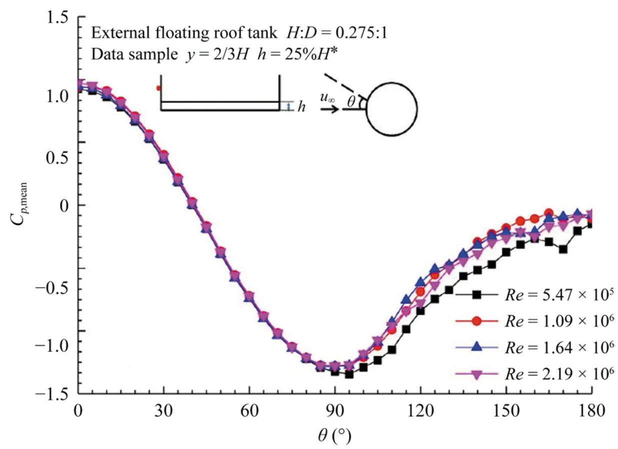


Fig. 7 The average pressure coefficients on the outer wall of the tank at different Reynolds numbers [67]

develop a stable and efficient algorithm. The influence of fine structural details on the wind-induced buckling of tank surfaces remains to be studied. Additionally, under the influence of eccentric wind forces, further research is needed to study potential bending, twisting, and deformation of oil and gas storage tanks.

3.3 Wind-induced interference effects

Three cooling towers of Ferrybridge Power Station in the UK collapsed at the allowable design wind speed of 18–20 m/s [70]. The investigation showed that the wind load on the downstream cooling tower was amplified due to the upstream adjacent cooling towers being too close together, resulting in the actual wind load on the downstream cooling tower exceeding the design value. In practical applications, oil and gas storage tanks are typically present in clusters, so it is necessary to conduct research on the wind-induced interference effects of oil and gas storage tanks.

Some researchers have evaluated the interference effects of gas tanks by base shear. Kang [71] and Li et al. [72] conducted wind tunnel force measurement experiments to study the impact of adjacent structures on the wind-induced base shear of gas tanks under different wind directions and spacing. They concluded that the magnitude of both the mean and fluctuating base shear of the gas tanks is influenced by the position of surrounding structures and the wind direction. To better assess the wind-induced interference effects on groups of oil and gas storage tanks, scholars conducted wind tunnel pressure measurement experiments. They studied the effects of different wind attack angles [73], arrangements and spacing [73–75] on the surface wind pressure distribution of the storage tanks. They found that the tank group effect causes changes in surface wind pressure, which in turn affects the buckling strength of the tanks [75]. Guo [54] conducted wind tunnel experiments to study the wind-induced interference effects of tank groups and found that the interference effects were significant when tanks were located downstream of interfering tanks. Uematsu et al. [76] studied the impact of layout and spacing on the wind pressure distribution of open-top storage tanks through wind tunnel tests and numerical simulations. They found that the arrangement patterns significantly affect the distribution of internal and external pressures on the surfaces of the

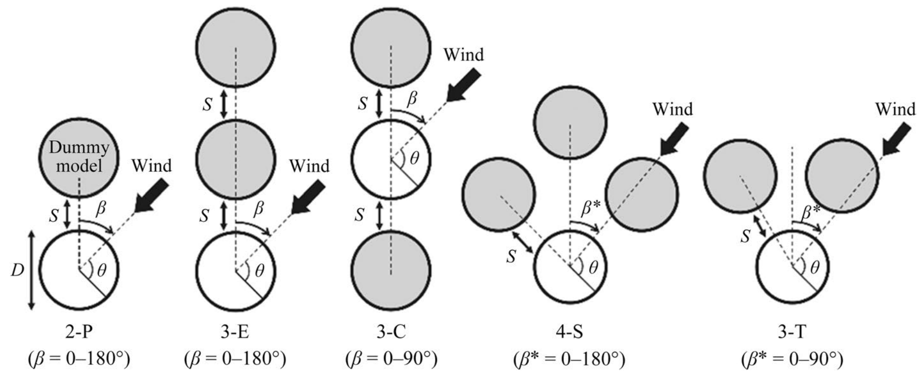


Fig. 8 The arrangement patterns of tanks affected by interference effects [76]

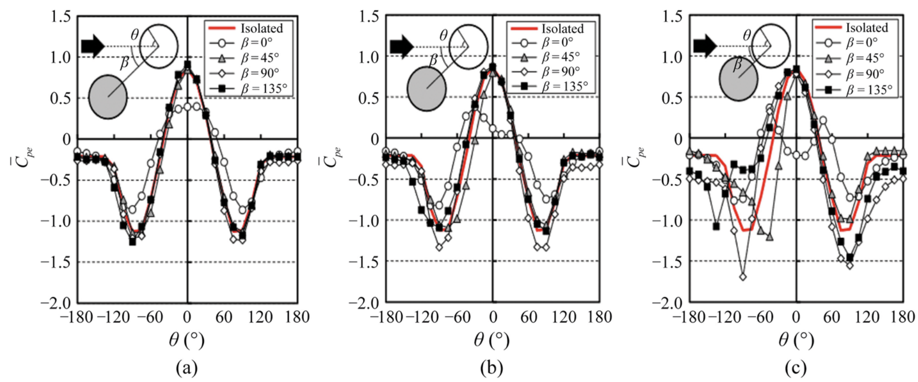


Fig. 9 Wind pressure coefficients for tanks at different spacing and wind angles [76] (From **a** to **c**, *S/D* is 1, 0.5, and 0.125, respectively)

storage tanks. The arrangement patterns of the storage tanks are shown in Fig. 8 [76]. The wind pressure coefficients of storage tanks at different spacing and wind angles are shown in Fig. 9 [76]. Based on Fig. 9, it is observed that when $S/D=1$, the distribution of C_{pe} closely resembles that on the isolated tank, except for $\beta \leq 30°$. As S/D decreases (as shown in the 2-P layout in Fig. 8), the differences in C_{pe} distribution compared to the isolated tank become more pronounced. In the wind direction range of $\beta=90°$ to 135°, the positive C_{pe} range in the windward area is relatively broad. Both spacing and wind direction angle affect the wind pressure distribution on the tanks.

Currently, research on the wind-induced interference effects of large oil and gas storage tanks primarily focuses on surface wind pressures and base shear. The wind-induced interference effects of oil and gas storage tanks are greatly affected by the arrangement and spacing, so it is necessary to optimize the group arrangement to reduce these interference effects. Current research primarily relies on rigid model experiments, neglecting the influence of fluid–structure coupling effects, which to some extent compromises the accuracy of the experiments. Oil and gas storage tanks are prone to local deformations under wind loads, yet there is limited research on how interference effects affect local wind pressures on their surfaces. Furthermore, there are few field measurements regarding interference effects, necessitating further field studies to validate the accuracy of wind tunnel experiments concerning wind-induced interference effects.

3.4 Structural dynamic characteristics

Obtaining the dynamic characteristics of oil and gas storage tanks is the basis for analyzing their wind-induced responses. Gu et al. [77] studied the dynamic characteristics of the Klonne gas tank through numerical simulation and field measurements, obtaining the first 20 order free-vibration characteristics. Some scholars [49, 78, 79] have studied the structural dynamic characteristics of gas tanks with the piston at different positions. They found that the fundamental vibration mode of gas tank is a cantilever beam vibration [78], the lower-order vibration modes are mainly the vibration of the body [79], and the structural frequency of the gas tank decreases as the piston rises [49, 79]. Liu et al. [80] conducted the design and testing of aeroelastic models of MAN-type dry gas tanks and found that the primary contributing modes to the wind-induced response are the first 10 modes, and the internal pressure of the tank has a relatively small effect on the structural vibration frequency. Yasunaga et al. [81, 82] analyzed the buckling and vibration characteristics of tanks under wind loads using the finite element method and discussed the impact of wind girders on the tank's modes. Amiri and Sabbagh-Yazdi [83] studied the impact of the tank roof on the natural frequency and vibration modes of storage tanks through ambient vibration tests and numerical simulations. They found that the tank roof has a minor effect on the natural vibration frequency but significantly influences the vibration modes of the storage tank. The axial vibration modes of the storage tank with a height-to-radius ratio of 2 are shown in Fig. 10 (corresponding to the results in Fig. 11a). This figure illustrates the first five order vibration modes of the storage tank. The axial vibration modes of storage tanks with different height-to-radius ratios are shown in Fig. 11. As the height-to-radius

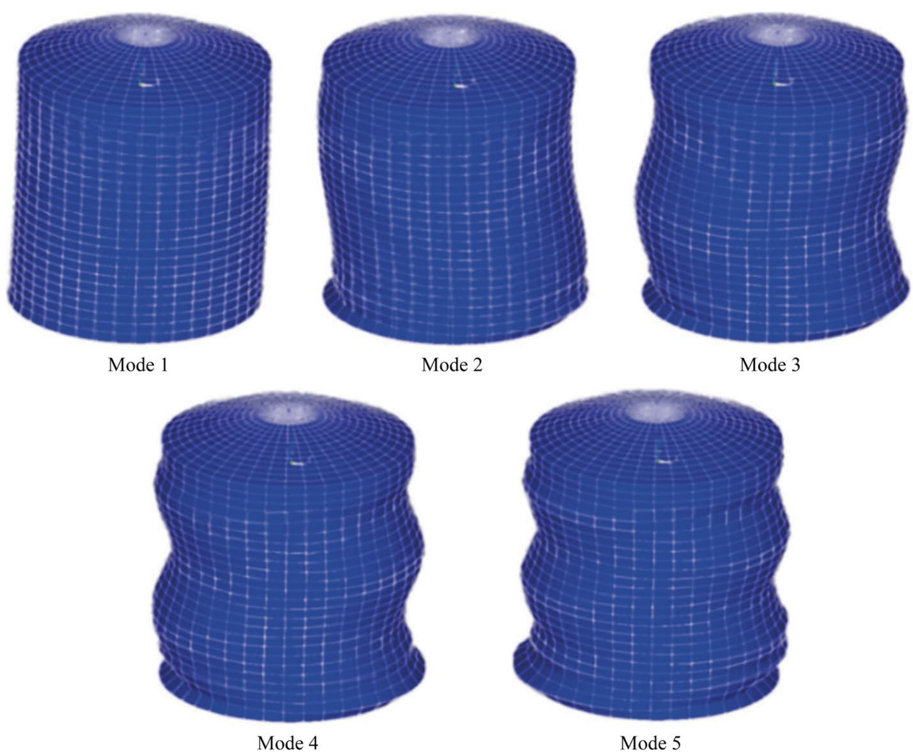


Fig. 10 Axial vibration modes of storage tanks [83]

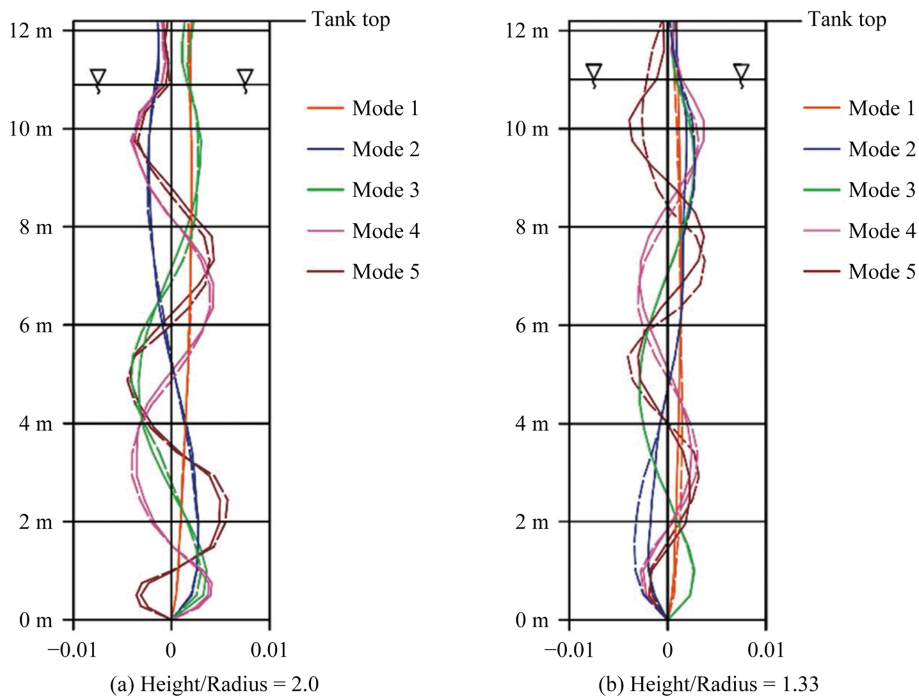


Fig. 11 Axial vibration modes of storage tanks with different height-to-radius ratios [83]

ratio decreases, the influence of the tank roof on the dynamic characteristics of the storage tank also decreases accordingly. The dashed and solid lines in Fig. 11 represent the results for the open-top and closed-top tank models, respectively. The mode differences between open-top and closed-top models vary with different height-to-radius ratios. The height-to-radius ratio also affects the degree of deformation constraint of the tank roof on the storage tank. Dehghan Manshadi and Maheri [84] studied the impact of corrosion and aging on the dynamic characteristics of cylindrical liquid storage tanks through numerical simulation. They found that corrosion significantly affects the fundamental vibration modes of the tanks.

Current research on the dynamic characteristics of large oil and gas storage tanks primarily relies on numerical simulations and wind tunnel tests, with few field measurements being conducted. The structure of large oil and gas storage tanks is quite complex, making it difficult for numerical simulations and wind tunnel tests to fully reflect the actual conditions. For instance, wind tunnel tests struggle to account for factors such as the position of the gas tank piston, internal pressure of the gas tank, and changes in liquid level inside the storage tank, all of which affect the structural dynamic characteristics. Numerical simulations are based on simplified models under certain conditions and need to be validated through field measurements. Therefore, it is necessary to conduct further field measurements to obtain the dynamic characteristics of oil and gas storage tanks.

3.5 Determination of wind loads

There are few studies on wind load calculation methods for oil and gas storage tanks. The standard values of wind load calculation for storage tanks are mainly based on the Load Code for the Design of Building Structures (GB 50009–2012) [85].

$$\omega_k = \beta_z \mu_s \mu_z \omega_0.$$

In the formula, ω_k is the standard values of wind load, kN/m^2; β_z is the wind vibration coefficient at height z; μ_s is the shape coefficient for wind load; μ_z is the height variation coefficient for wind pressure; ω_0 is the basic wind pressure, kN/m^2.

The shape coefficient for wind load depends on the shape and scale of the structure [85]. The wind-induced vibration coefficient depends on factors such as the scale of the oscillating structure, natural frequencies, structural configuration, and ground roughness. The standards do not specify values for wind vibration coefficients or shape coefficients for large oil and gas storage tanks. To accurately calculate wind loads on large oil and gas storage tanks, researchers have studied wind vibration coefficients and shape coefficients specific to these tanks. Dan [86] assumed that the wind vibration coefficient of the storage tank varies continuously with height. He obtained the vibration coefficient at different relative heights through least squares fitting to derive the calculation formula for the wind vibration coefficient. Liu et al. [87] conducted wind tunnel tests using an aeroelastic model to analyze the fluctuating wind effects on the gas tank, and proposed a wind vibration coefficient calculation formula suitable for gas tanks. The calculation formula of wind vibration coefficient is shown in Table 4.

Li [49] studied the shape coefficient of gas tanks with a height-diameter ratio of approximately 2. He found that the wind pressure shape coefficient provided in the standards for cylindrical structures was higher than the measured values, indicating that the standard value was conservative in engineering applications. Dan [86] analyzed the wind pressure shape coefficients on the surfaces of cylindrical tanks and hyperbolic cooling towers. Referring to the standards, he proposed a calculation formula for the wind pressure shape coefficient of the gas tank as a whole.

$$C = 1.114 - 0.314 \times \frac{2n - 8}{20}.$$

In the formula, C is the wind load shape coefficient for overall calculation; $2n$ is the number of sides of the gas tank body.

For calculating the wind pressure shape coefficient of large oil storage tanks, researchers typically use wind tunnel tests and fit the test data using Fourier series to derive analytical expressions.

Scholars have conducted research on the wind load shape coefficients of oil storage tanks, summarized in Table 5.

Table 4 Formulas for calculating the wind vibration coefficient of gas tanks

Documents	Formulas	Explanation of parameters
Load code for the design of building structures [85]	$\beta_z = 1 + 2gI_{10}B_z\sqrt{1+R^2}$	g is the peak factor, which can be 2.5; I_{10} is the nominal turbulence intensity at a height of 10 m; B_z, R are the background component factor and resonance component factor of pulsating wind loads, respectively
Dan [86]	$\beta_z = 0.95 + 1.125(\frac{Z}{H})$	Z is the height of the measuring point, and H is the total height of the gas tank
Liu et al. [87]	$\beta_z = -0.36(\frac{Z}{H}) + 1.647$	

$$\mu_s(\theta) = \sum_{i=0}^{n} k_i \cos(i\theta).$$

In the formula, $\mu_s(\theta)$ is the shape coefficient, n is the number of terms in the cosine series, k_i is the Fourier coefficient, and θ is the arc angle.

The methods described above for calculating wind vibration coefficients and shape coefficients are primarily based on specific conditions, such as assuming continuous variation of wind vibration coefficients with height, relying solely on wind tunnel tests without field verification, linearly approximating parameters according to standards, assuming height-to-width ratios, and simplifying to rigid models for shape coefficients. These formulas serve as approximate calculation methods. Accurate calculation of wind loads on large oil and gas storage tanks requires further research and refinement.

3.6 Multiple load effects

During operation, oil and gas storage tanks are not only affected by wind loads but also by other factors such as earthquakes, waves, settlement, and various other influences. Bernier and Padgett [91] used numerical simulations to study the buckling behavior of above-ground storage tanks under storm surges and wave loads, discussing the impact of dynamic loading effects on buckling behavior. Jing et al. [92] conducted numerical simulations to study the dynamic response of tanks with different storage-capacity ratios under wind-earthquake conditions. They found that tanks with a larger capacity ratio are more likely to be damaged under the combined effects of wind and strong earthquakes. Ramírez Olivar et al. [93] conducted a vulnerability study of storage tanks under extreme wind conditions. The results can provide a reference for risk assessment of storage tanks in related disasters. Chen et al. [94] used numerical simulations to study the thermal buckling behavior of steel vertical dome storage tanks under the combined effects of static wind load and thermal effects. They found that thermal buckling is more severe in the downwind direction. Sun et al. [95] established a finite element model to investigate the wind-induced buckling of storage tank shells with harmonic settlement defects. They discussed the impact of harmonic settlement-induced defects and wind attack angles on the wind buckling resistance of storage tanks. Zuluaga Mayorga et al. [96] developed limit state equations for the buckling failure of storage tanks under the effects of floods, earthquakes, and hurricanes, respectively. Huang et al. [97] developed limit state equations for the buckling failure of storage tanks under the combined action of floods and hurricanes. They compared and analyzed the buckling failure probabilities of vertical tanks under the separate effects of floods or hurricanes, their direct superposition, and their coupled effects. The pressure analysis of the buckling failure of vertical tanks under the combined action of floods and hurricanes is shown in Fig. 12. Under the combined action of floods and hurricanes, the external pressure on the tank wall includes wind load, hydrostatic pressure from the flood, dynamic pressure from fluid, and wave load caused by the hurricane.

Large oil and gas storage tanks are mostly built in coastal areas with poor geological conditions and may be affected by wind loads, storm surges, waves, settlement, and earthquakes. Existing studies mainly focus on numerical simulations of wind-earthquake and wind-settlement interactions. There is relatively less research on the structural

Table 5 Fourier coefficients of storage tanks

Documents	Height/Width	k_0	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8
Rish [88]	/	−0.387	0.338	0.533	0.471	0.166	−0.066	−0.055	/	/
Guo [54]	0.556	0.549	0.353	0.483	0.335	−0.060	−0.032	0.022	−0.027	−0.013
	0.332	0.365	0.380	0.420	0.324	−0.066	−0.037	0.061	−0.017	−0.025
	0.204	0.223	0.540	0.408	0.229	−0.023	−0.043	0.011	0.021	0.003
Portela and Godoy [56]	0.15	−0.1925	0.3708	0.5612	0.2297	−0.0263	−0.0168	−0.0062	−0.0288	/
	0.23	−0.1917	0.3161	0.5001	0.2475	−0.0404	−0.0114	0.0599	0.0266	/
Lin [89]	0.275	−0.232	0.328	0.610	0.268	−0.082	−0.038	0.033	−0.014	−0.003
EN1993 [90]	$\mu_s(\theta) = -0.54 + 0.16\gamma + (0.28 + 0.04\gamma)\cos\theta + (1.04 - 0.20\gamma)\cos 2\theta + (0.36 - 0.05\gamma)\cos 3\theta - (0.14 - 0.05\gamma)\cos 4\theta, \gamma = D/H$									

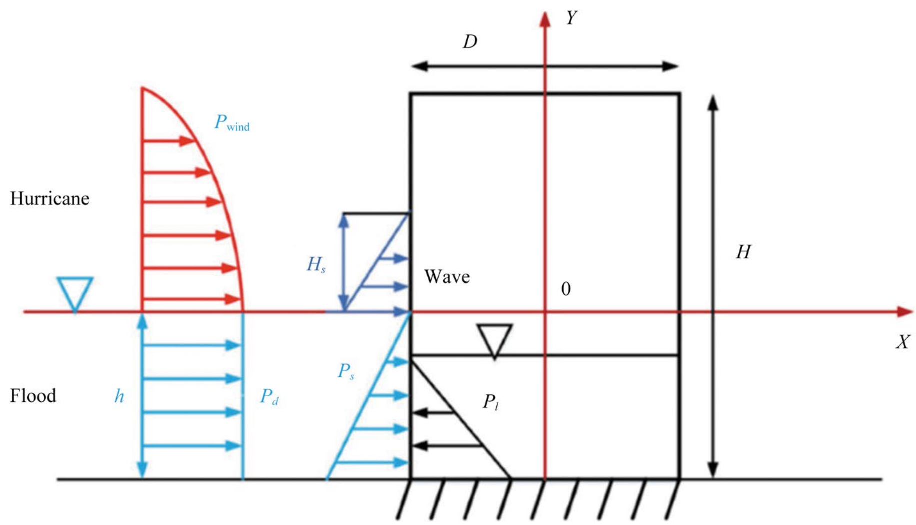


Fig. 12 The pressure analysis of buckling failure in vertical storage tanks under the combined action of floods and hurricanes [97]

response of oil and gas storage tanks under the combined effects of wind, earthquake, settlement, and waves. Therefore, it is necessary to continue studying the buckling resistance of large oil and gas storage tanks under multiple effects to ensure their safe operation in extreme environments. Future research can combine macro-scale and micro-scale simulations and experimental methods to study the mechanical properties and failure mechanisms of storage tanks under various loads, providing a more precise and dependable theoretical foundation for wind-resistant design.

4 Wind-resistant safety guarantee measures for large oil and gas storage tanks

4.1 Wind resistance of storage tanks based on wind beam reinforcement

The main structure of oil and gas storage tanks consists of thin-shell steel, which is prone to local vibration and deformation under wind loads. Conducting research on vibration reduction and wind-induced vibration control is of great significance for mitigating wind-induced damage to these tanks. Common wind-resistant reinforcement measures for storage tanks include wind beams and stiffening ribs, which can resist deformation and buckling of the shell wall caused by wind loads [98]. Wang [5] studied the impact of circumferential stiffening ribs, wind rings, and longitudinal stiffening ribs on the wind resistance performance of storage tanks. The study revealed that circumferential stiffening ribs and wind rings respectively affect the local stability and overall stability of the storage tanks, while vertical stiffening ribs are less effective against wind compared to circumferential stiffening ribs and wind rings. Bu et al. [65, 66] developed a three-dimensional finite element model to study the reinforcement effect of wind girders on storage tanks. They found that the addition of wind girders altered the buckling mode of the tank, thereby improving the buckling resistance of the tank wall. They also conducted an optimization analysis to minimize the weight of the wind girders for a given wind load and provided calculation formulas for the size and spacing of the wind girders. Sun et al. [99] studied the impact of wind beams on the wind-induced buckling of open-top storage tanks and found that wind beams can significantly suppress buckling deformation and increase the critical buckling load. Based on cylindrical shell buckling theory and existing calculation methods, they proposed an empirical formula for the critical buckling wind pressure of open-top tanks with varying numbers of wind beams within the boundary layer. The buckling eigenvalues of tanks reinforced with different numbers and sizes of wind beams are shown in Fig. 13. ϕ represents the ratio of wind girder stiffness to tank wall stiffness. As ϕ increases, the buckling eigenvalues increase, and the location of maximum displacement gradually moves downward. When ϕ reaches a critical value, the eigenvalues remain nearly constant and become independent of ϕ. Pan and Liang [100] investigated the effects of wind girders, other reinforcement devices, and stored liquid on the buckling performance of storage tanks. The results showed that the reinforcement devices and stored liquid respectively enhanced the stiffness of the top and bottom of the storage tanks, thus affecting their buckling behavior. Liang et al. [101] proposed a reinforcement scheme involving arches, I-beams, and channel steel to improve the stability of tank roofs. The results showed that using a combination of steel structures and composite materials enhanced the stability of the tank roofs.

Research on the wind resistance of large oil and gas storage tanks is mainly conducted through numerical simulation. The study investigates the impact of reinforcement devices such as wind girders and stiffeners on the wind resistance of storage tanks. The stiffness, size, quantity, arrangement spacing, and position of these reinforcement devices all affect the wind resistance of the storage tanks. There is limited research on the vertical stiffening ribs of storage tanks. Although vertical stiffeners are less effective in wind resistance compared to horizontal stiffeners, they are more economical for large-diameter storage tanks. Therefore, further research should focus on identifying the best combination and layout of wind girders for storage tanks under various conditions to achieve optimal wind resistance.

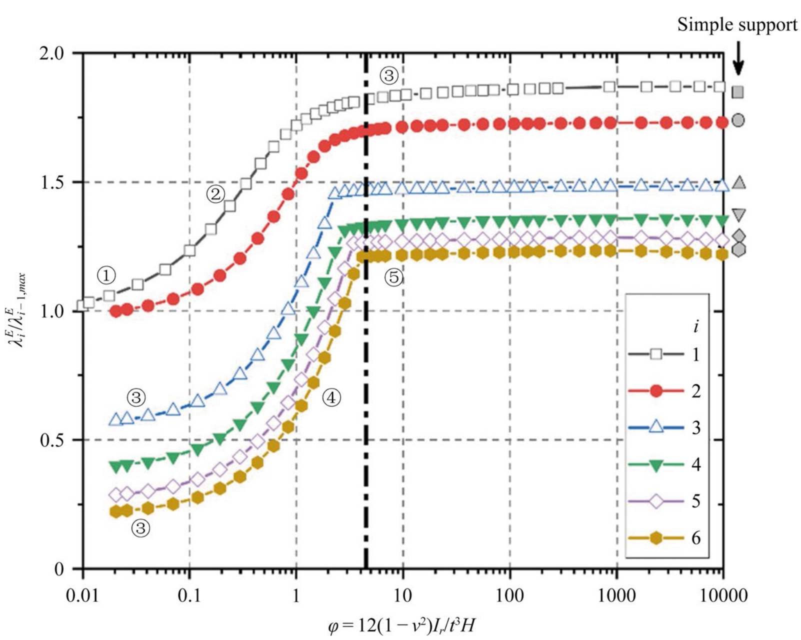
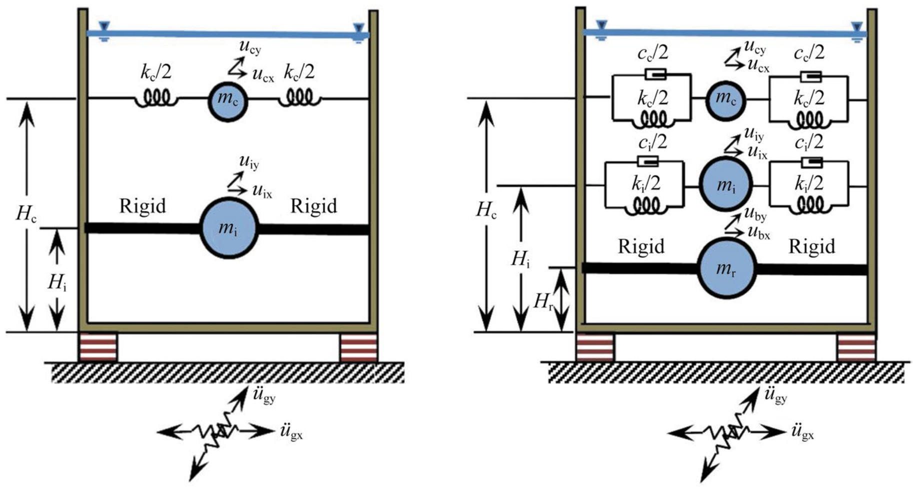


Fig. 13 The buckling eigenvalues of tanks reinforced with different numbers and sizes of wind beams [99]

4.2 Vibration reduction of storage tanks based on foundation isolation

Earthquakes occur frequently worldwide, and the vibrations caused by earthquakes can lead to damage such as buckling of the tank walls. De Angelis et al. [102] studied the effectiveness of base isolation for steel storage tanks through numerical simulations and shake table tests. They found that isolators effectively reduced the pressure on the tank walls but had no control over the wave height.

Saha et al. [103] studied the impact of different isolation parameters, such as characteristic strength and yield displacement of isolators, on the seismic response of base-isolated liquid storage tanks. Sun et al. [104] used ADINA to create a finite element model to study the seismic response of base-isolated floating roof tanks under different isolation damping ratios, isolation periods, intensities, and site conditions. The results indicated that the seismic mitigation effectiveness of the isolated tanks is closely related to the isolation period and the damping ratio of the isolation layer. However, base-isolated tanks cannot control the sloshing wave height. Li et al. [105] proposed a new flexible bottom plate connection base-isolated tank structure and analyzed its seismic mitigation effects. The results showed that this isolation device can effectively reduce the base shear and overturning moment of the tank during an earthquake, but it has limited control over the sloshing wave height of the stored liquid. Nikoomanesh et al. [106] proposed a new seismic isolation method for storage tanks. Numerical simulation results showed that this system can significantly reduce the overturning moment of liquid storage tanks, with a more pronounced isolation effect for slender tanks. Rawat et al. [107] used finite element analysis on base-isolated storage tanks with rigid and flexible walls of different parameters and found that increasing the isolation period can significantly reduce the base shear of the tank but increase the liquid sloshing. The mechanical models for base-isolated tanks with rigid and flexible foundations are shown in Fig. 14. In the two-mass rigid model in Fig. 14a, the liquid in the tank is divided into convective mass (m_c) and impulsive mass (m_i). The impulsive mass (m_i) is rigidly connected to the tank wall and primarily affects the base shear force on the tank wall. In the three-mass flexible model in Fig. 14b, the liquid in the tank is divided into convective mass (m_c), impulsive mass (m_i), and rigid mass (m_r). The convective mass (m_c) is connected to the tank wall through a convective spring, causing the liquid sloshing phenomenon. Safari and Tarinejad [108] employed frequency domain stochastic methods to study the dynamic response of base-isolated liquid storage tanks under near-fault and far-fault ground motions. The results showed that the isolation system significantly reduces the sloshing response of the tank. Panchal and Jangid [109] investigated the seismic performance of liquid storage tanks equipped with Variable Curvature Friction Pendulum System (VCFPS) under near-fault seismic excitation. The results showed that the VCFPS is quite effective in controlling the seismic response, including the base shear, sloshing displacement and impulsive displacement of liquid storage tanks. Bagheri and Farajian [110] studied the seismic performance of cylindrical liquid storage tanks isolated with Friction Pendulum System (FPS). The results showed that FPS is an effective isolation system, capable of reducing seismic responses such as impulsive displacement, overturning moment, and base shear of the tanks. Soni et al. [111] studied the seismic response of steel liquid storage tanks with Double Variable Frequency Pendulum Isolators (DVFPI) under 20 sets of ground motions. They analyzed the changes in base shear, convective displacement,



(a) Two-mass rigid model (b) Three-mass flexible model

Fig. 14 The mechanical models for base-isolated tanks with rigid and flexible foundations [107]

impulsive displacement, isolator displacement, input energy, and recoverable energy for four isolator design combinations. Goudarzi and Alimohammadi [112] used finite element models to investigate the seismic response of cylindrical liquid storage tanks with different height-to-radius ratios. They compared the responses of base shear, overturning moment and free surface displacement between isolated and non-isolated tanks, and found that isolated tanks have better isolation effects, but limited control over the wave height of liquid sloshing. Cheng et al. [113] used ADINA software to study the dynamic response of three storage tanks with different volumes and liquid heights under seismic action. They analyzed the sloshing wave height, peak acceleration of the tank wall, and hydrodynamic pressure. The results showed that as the liquid height increased, the peak sloshing wave height generally tended to rise, and the top of the tank was more likely to be damaged by the sloshing liquid. Zhou et al. [114] investigated the impact of different types of seismic waves on the dynamic response of wooden cylindrical storage tanks through shaking table tests and ADINA numerical simulations. They found that the sloshing amplitude of the liquid was greater under long-period seismic waves. Luo et al. [115] proposed a hybrid method to simultaneously adjust the structural mass, stiffness, and damping to reduce seismic-induced tank sloshing. By applying this method, both the amplitude of liquid sloshing in the tank and the overturning moment of the tank are reduced.

Large oil and gas storage tanks are mostly located in coastal areas with poor geological conditions, which necessitates considering the wind-induced soil-pile-structure interaction under strong winds or typhoons. Soil-structure interaction can cause soil loosening, affecting the structure's load-bearing capacity. It also alters the fixed state of the structure, reducing the stiffness at the fixed end and lowering the natural frequency of the entire structure, making it more prone to resonate with the wind and thus more susceptible to damage. Under strong winds or typhoons, storage tanks may also experience overall overturning. Additionally, coastal areas may face multiple loads such as strong winds and earthquakes acting simultaneously on the tanks. Current wind girder reinforcement measures cannot effectively reduce the base shear of storage tanks under these conditions. Extensive research has been conducted on the seismic vibration reduction of storage tanks, primarily using shaking table tests and numerical simulations to study the effectiveness of different types of isolators. Factors such as isolation period, damping ratio of the isolation layer, characteristic strength of the isolator, and yield displacement all affect the vibration reduction performance of base-isolated storage tanks. Base isolation measures can effectively reduce the impulsive displacement, sloshing displacement, base shear, and overturning moment of storage tanks. Therefore, the seismic vibration reduction methods for storage tanks can be applied to reduce base shear and overturning moment under strong wind or typhoon conditions.

4.3 Liquid sloshing reduction in storage tanks using baffles

Under strong wind or earthquake conditions, the vibration of the storage tank can cause the liquid inside to slosh. Adding wind beams and conventional isolation measures on the tank cannot control the sloshing of the liquid inside. Researchers have introduced baffles inside the tanks to control the sloshing wave height of the liquid under strong wind or earthquake conditions. Hosseini et al. [116] conducted shake table tests to study the effect of annular baffles inside the tank on the sloshing of liquid at different liquid levels. They found that the annular baffle can effectively control the sloshing height of liquid. Shekari [117] studied the effect of annular baffles on liquid sloshing in storage tanks through numerical simulations, investigating the impact of different baffle widths, positions and flexibilities on liquid sloshing. The tank model with baffles is shown in Fig. 15. Cho et al. [118] studied the dynamic response of liquid tanks with baffles through numerical simulations. The results showed that the baffles significantly reduced the displacement of the liquid at the bottom and near the baffles. Fang et al. [119] conducted shake table experiments to investigate the influence of annular baffles on liquid sloshing. They found that the sloshing wave height can be effectively suppressed when the baffle width and position are within a certain range. Baghban et al. [120] studied the influence of annular and horizontal baffles on the dynamic response of tanks under seismic action through numerical simulations. They found that the maximum base shear of the tank was reduced after using the baffle. Gopalakrishnan et al. [121] used numerical simulations to study the impact of baffle position on liquid sloshing in storage tanks and identified the optimal baffle position for the tank. Hosseinzadeh et al. [122] conducted shake table experiments to study the dynamic characteristics of tank models with different liquid levels and baffle sizes. They found that annular baffles were significantly effective in reducing the sloshing height of the liquid.

Currently, there is limited research on wind resistance and vibration reduction for large oil and gas storage tanks. A few studies, based on numerical simulations, have investigated the impact of reinforcement devices such as wind girders and stiffening ribs on the wind resistance of storage tanks. The stiffness, size, number, and position of these reinforcement devices affect the tanks' wind resistance. It is necessary to configure wind girders under different conditions to improve wind resistance. Large oil and gas storage tanks are mostly built in coastal areas with poor geological conditions. Under strong winds or typhoons, the wind-induced interaction between the soil, pile, and structure is significant, posing a risk of tank overturning. Current wind

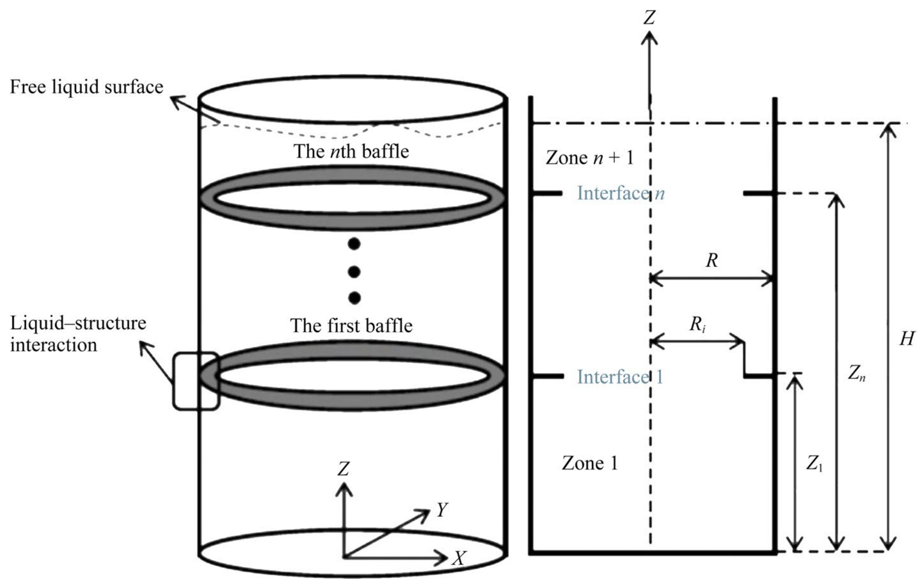


Fig. 15 Multi-baffle tank model [117]

girder reinforcement measures cannot effectively reduce the overturning moment of storage tanks under these conditions. Extensive research has been conducted on the seismic vibration reduction of storage tanks, showing that base isolation measures can effectively reduce base shear and overturning moments. Therefore, these seismic vibration reduction methods can be applied to decrease the base shear and overturning moments of storage tanks under strong winds or typhoons. To address the issue of liquid sloshing, many researchers have studied the use of annular baffles to control the sloshing wave height. They focused on factors such as baffle width, position, and flexibility, and found that when the width and position of the annular baffles are within a certain range, they can effectively control the sloshing height of the liquid. In regions prone to frequent typhoons or strong winds, it is necessary to study the applicability of earthquake mitigation methods and ideas for wind vibration reduction in storage tanks. For example, by modifying the material parameters and installation methods of existing isolation bearings or dampers, we can study their effectiveness in simultaneously reducing wind-induced and seismic vibrations. Additionally, researching the effectiveness of baffles or other structural measures in mitigating wind-induced liquid sloshing can be explored.

5 Summary and future perspectives

Scholars have studied the flow field characteristics, wind load properties, wind-induced responses, and wind resistance measures of large oil and gas storage tanks under wind loads, leading to significant findings. However, current research still has some limitations. It is necessary to systematically study the wind effects on large oil and gas storage tanks under different wind conditions by combining field measurements, aeroelastic model wind tunnel tests, fluid–structure interaction numerical simulations, theoretical analysis, and machine learning. This will provide references for the wind-resistant design and safety assurance of large oil and gas storage tanks. A further summary and perspectives are as follows.

(1) **Accurately obtain the near-surface wind field characteristics of the incoming flow and within the tank group.** Obtaining the near-surface wind field characteristics at the location of storage tanks and within the tank group is essential for providing reliable wind field parameters for numerical simulations and wind tunnel tests. This is the basis for accurately assessing wind loads and wind effects on oil and gas storage tanks and for developing appropriate wind-resistant designs. Traditional wind measurement towers have fixed measurement positions and limited height arrangements, making it difficult to comprehensively capture the characteristics of the entire three-dimensional wind field where tank clusters are located. The unmanned aerial vehicle (UAV) wind measurement systems offer significant advantages in measuring complex terrain wind profiles, planar wind fields, and three-dimensional wind fields. As a cylindrical structure, tanks experience significant wake shedding, which in turn leads to notable disturbance in the flow field within tank clusters. Utilizing UAV wind measurement systems allows for capturing the actual wake characteristics of tanks and the interference patterns within the cluster's flow field. By assessing the impact of measured wake on downstream tanks, numerical models can be optimized to more accurately simulate wake effects, thereby improving the layout design of tank clusters. It is recommended to use a combination of UAV wind measurement systems, wind measurement towers, and wind measurement masts to accurately obtain the near-surface wind field characteristics of incoming flows and within the tank group.
(2) **Improve the study of wind effects on tanks under different wind conditions.** Conducting a systematic study of wind effects on storage tanks to understand the wind pressure distribution and wind-induced buckling characteristics on their surfaces will provide guidance for the wind-resistant design and reinforcement measures of storage tanks. Field measurements are the most direct and reliable method for studying wind effects on structures. By conducting field measurements, we can obtain the wind pressure distribution and wind-induced response characteristics on the surfaces of storage tanks. This allows us to determine the dynamic characteristics, wind vibration coefficients, and shape coefficients of large oil and gas storage tanks, and to verify the results of wind tunnel tests and numerical simulations (since wind tunnel tests may not accurately reflect the effects of Reynolds number, and numerical simulations often involve simplified conditions). These results provide a basis for establishing wind-resistant design theories for large oil and gas storage tanks. Therefore, it is necessary to further conduct field measurements of wind effects on oil and gas storage tanks in different regions and wind environments, such as strong typhoons, tornadoes, and severe convective weather. Large oil and gas storage tanks are thin-walled structures, making them susceptible to wind-induced vibrations. It is necessary to conduct aeroelastic model wind tunnel tests and numerical simulations that consider fluid–structure interactions. By comparing the wind pressure distribution and flow field characteristics around the surfaces of oil and gas storage tanks using both rigid and aeroelastic models, we can investi-

gate the impact of fluid–structure interactions on surface wind pressure and flow field. Additionally, comparing the experimental results with field measurements using fractal theory can improve the reliability of wind tunnel tests and numerical simulations. In existing wind tunnel tests, the impact of external components such as stairs and railings is rarely considered. These components can affect the wind pressure distribution and the surrounding flow field, which in turn influences the wind-induced vibrations of thin-walled storage tanks. Additionally, as storage tanks resemble cylindrical structures, the Reynolds number effect cannot be ignored. Therefore, when conducting wind tunnel tests, it is necessary to treat the surface roughness of the model to minimize the impact of the Reynolds number as much as possible.

(3) **Improve the study of wind-induced interference effects on groups of storage tanks.** It is necessary to consider the fluid–structure interaction and systematically study the effects of parameters such as wind direction angles, number of tanks in a group, spacing between tanks, arrangement patterns, and interference model dimensions on the internal flow field and wind-induced interference effects in storage tank groups. This will help optimize the layout of storage tank groups. Additionally, oil and gas storage tanks, being similar to cylindrical thin-walled structures, experience significant vortex shedding under wind loads. Due to their relatively low local stiffness, they are prone to crosswind-induced local wind vibration responses. Therefore, it is necessary to study the impact of interference effects on these local wind vibration responses.

(4) **Enhance the study of multi-load coupling effects on storage tanks.** In coastal areas, strong winds often accompany heavy rain, and the additional loads from wind and rain interactions are more likely to damage thin-walled structures like storage tanks. Existing research primarily focuses on the impact of wind alone, so it is necessary to study the effect of wind-driven rain on the safety performance of storage tanks. Additionally, storage tanks in coastal areas may be affected by multiple coupled forces such as wind loads, storm surges, waves, ground settlement, and earthquakes during their service life. In tropical island regions, it is also necessary to consider the combined effects of high temperatures, high humidity, high salt spray, high UV radiation, and strong typhoons on storage tanks. Therefore, it is essential to conduct more detailed multi-hazard analyses on storage tanks and propose performance-based multi-hazard protection design methods.

(5) **Enhance wind-resistant safety measures for storage tank structures.** Existing studies have explored the impact of wind beams, stiffeners, and other reinforcement devices on the wind resistance of storage tanks. Horizontal stiffeners offer better wind resistance for storage tanks than vertical stiffeners. However, vertical stiffeners are more cost-effective for large-diameter tanks. Therefore, it is essential to balance economy and safety by considering the advantages of both horizontal and vertical stiffeners. Large oil and gas storage tanks are mostly built in coastal areas with poor geological conditions. Under strong winds or typhoons, the wind-induced interaction effects between the soil, pile, and structure are significant, posing a risk of tank overturning. Current wind beam reinforcement measures cannot effectively reduce the base shear force caused by strong winds or typhoons. There-

fore, in regions frequently affected by strong winds or typhoons, it is necessary to apply seismic damping methods and approaches to enhance both wind resistance and seismic damping in storage tanks. For example, by modifying the material parameters and installation methods of existing isolation bearings or dampers, we can study their effectiveness in simultaneously reducing wind-induced and seismic vibrations. Additionally, researching the effectiveness of baffles or other structural measures in mitigating wind-induced liquid sloshing should be explored.

(6) **Prospects for wind-storage tank interaction research.** There are many research scopes for researchers in studying the nonlinear response of large storage tanks, wind-induced soil-tank interaction, wind-induced responses of tanks under extreme winds (such as thunderstorms and tornadoes), and the effects of different terrain conditions, storage volumes of liquids or gases, and tank wall defects caused by corrosion on wind effects. In addition, numerous factors influence the wind loads on individual storage tanks and tank groups (such as tank height-to-diameter ratio, spacing, layout, wind direction angles, surrounding environment, and wind conditions). Conducting wind tunnel tests or numerical simulations for each condition consumes considerable time and economic resources. Machine learning excels at extracting complex physical features from large datasets. Machine learning can be used to study tank flow characteristics and predict extreme wind pressure and aerodynamics for individual tanks and tank groups, ensuring wind-resistant safety assurance in different environments.

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Authors' contributions
Bin Huang designed the framework of this paper, and was a major contributor in writing the manuscript & supervision. Xijie Liu: Writing-original draft, review & editing. Zhengnong Li: Supervision, review & editing. Dabo Xin: Review & editing. Jinke Liu: Investigation & polishing. Shujie Qin: Language polishing & editing. Tianyin Xiao: Investigation & polishing. Jinshuang Dong: Formal analysis & polishing.

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Declarations

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The authors declare that they have no competing interests.

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